

Modelling the flare activity of Sgr A*

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Abstract.

Latest observational data provides evidence that the emissions from Sgr A* originate from an accretion disc within ten gravitational radii of the dynamical centre of Milky Way. We investigate the physical processes responsible for the variable observed emissions from the compact radio source Sgr A*. We study the evolution of the variable emission region and analyse light curves and time-resolved spectra of emissions originated at the surface of the accretion disk, close to the event horizon, near the marginally stable orbit of a Kerr black hole.

Keywords: Sgr A*, Light curve, Hot spot, Black hole physics, Galactic Center, Accretion disc, Relativity effects

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INTRODUCTION

Recent studies of the inner few parsecs at the centre of our Galaxy provide clear indications of a supermassive black hole, object associated with the unusual, non-thermal, variable radio source Sgr A*. The highly compact nature of the distributed mass and the intense gravitational field suggest the presence of dark matter.

Sgr A* shows the feature of so-called flares, short bursts of increased emission that last for about 20-100 min, suggesting that the emitting region is located very close to the black hole. We investigate light curves from an emitting, variable hot spot co-moving with the accretion disk. Using relativistic ray-tracing methods, we produce time-resolved images and spectra of the accretion emission region, as seen by an observer located at infinity. The disk model is supposed to be keplerian, geometrically thin and optically thick in Kerr geometry.[21]

There is evidence that the emissions from Sgr A* originate from the accretion disc from within only a few gravitational radii from the black hole centre. In order to understand the physics behind the observed time-dependent processes, we model light curves and spectra of emissions originated at the surface of the accretion disk, close to the event horizon, near the innermost stable circular orbit (ISCO) of a Kerr black hole. [3] As seen in Figure 1, the photon trajectories originated at the surface of the accretion disk, near the last stable orbit, are calculated. This allows us to explore different emission models and various characteristics of the black hole. The observed spectra depend on the radiation emitted from the accretion disc and it is influenced by the strong gravity field on its way to infinity.[7] The flux from an accretion disk mostly originates from the innermost regions, where relativistic effects are very important for our understanding of the observed variability patterns.[19] Relativistic effects play a crucial role, especially in the time-dependent behaviour and particularly for a maximally rotating Kerr black

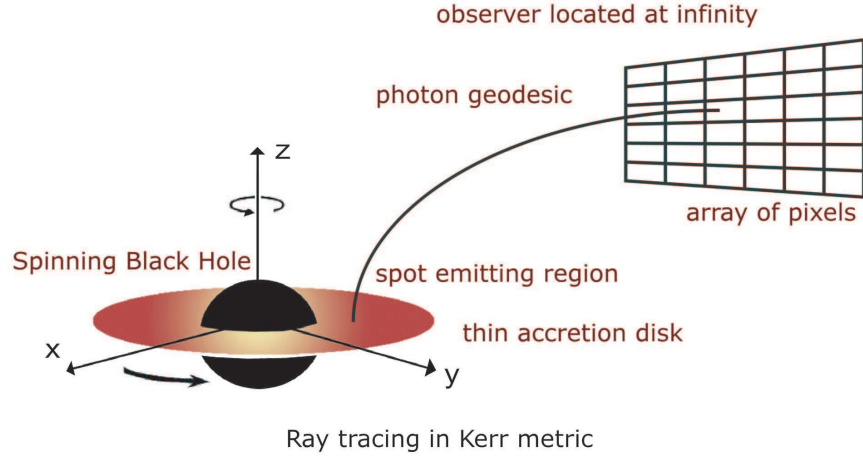


FIGURE 1. Ray tracing in Kerr geometry

hole.[10]

We take into account all relativistic effects such as light bending, gravitational lensing, redshift and time dilation. The variations in the redshift are evident in the spectrum shown in Figure 6. Using relativistic ray-tracing techniques, we analyze the constraining parameters and characteristics of the black hole and study the major imprint of both special and general relativistic effects on the time dependent observed phenomena. [20]

By integrating the photon geodesics between a position inside a spot and a distant observer, we obtain time resolved spectra for both orbiting and infalling spots co-moving with the accretion disk, in a strong gravitational field. An example of a time dependent spectrum for a plunging spot can be seen in Figure 2. We explore the evolution of the emission region, close to the event horizon and diagnose light curves for various spectral emissivity profiles, different viewing directions of the distant observer and different locations of the spot relative to the distant observer, the event horizon and the center of the black hole. The emissivity is a function of both radial and polar parameters. The spot lightcurves may be interpreted as regions of enhanced emission in the local frame, near above the last stable orbit. Figure 3 is an example of a plunging trajectory of an infalling spot, the light curve of which is shown in Figure 4.

MOTIVATION

Due to its proximity, SgrA* provides favorable circumstances to a better understanding of the processes responsible for the observed time-dependent phenomena. Apparently, the emissions from Sgr A* are originated in radiative processes in keplerian motion, with a peak occuring within several Schwarzschild radii ($r_S \equiv 2GM/c^2$) of the centre. [26]

Latest theoretical models are trying to address the question of what the spectral line profiles or continuum may tell us about the black hole properties, and analyze

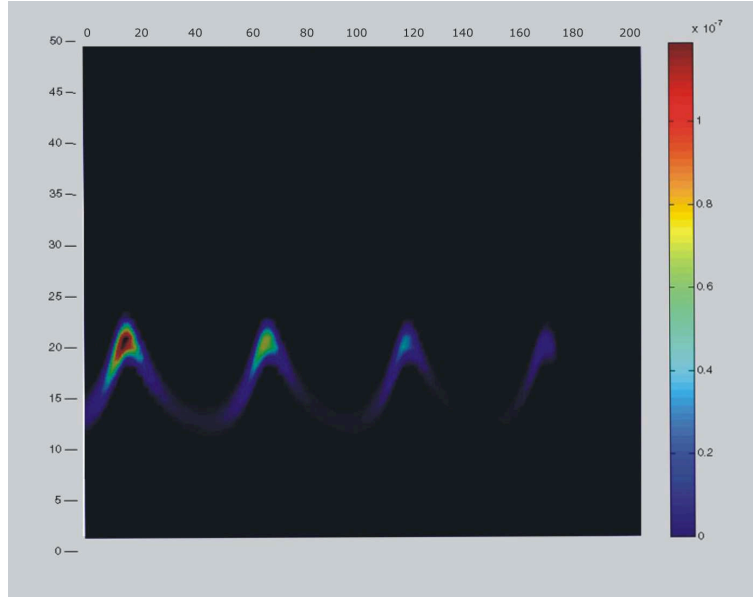


FIGURE 2. Time-dependent spectrum of a spot falling from the ISCO down towards the Kerr black-hole event horizon. Energy is on the ordinate, time on the abscissa

the constraining parameters and characteristics of the accretion disc close to the event horizon. [13] We take into account emissions from within the last stable orbit of a rotating black hole and from the region near above the marginally stable orbit.[2]

BASIC ASSUMPTIONS AND OBJECTIVES

We consider a complete system comprising a black hole, an accretion disc and a co-rotating spot within the cold accretion disk. [11] The gravitational field is described in terms of Kerr metric[22], for a rotating black hole and particularly for a non-rotating black hole, in Schwarzschild metric.[23]. Figure 5 exemplifies the differences between the spectra obtained in Kerr and Schwarzschild metrics. The co-rotating Keplerian accretion disc is geometrically thin and optically thick, therefore we take into account only photons coming from the equatorial plane directly to the sky plane. The spot is orbiting within the disk near the rotating black hole.[9]

A relativistic ray tracing code is used to analyze how the considered effects affect the disk emissions originated in a co-moving (local) frame with the accretion disk, up to a observer located at infinity and placed in the azimuthal direction $\varphi = \pi/2$. [5] Relativistic effects alter the shape of the resulting spectra, more significantly at large inclination angles and play an important role in the time-dependent emission processes, especially in the case of a maximally rotating Kerr black hole.[15] The code is used with the standard X-ray spectral fitting package, XSPEC (Arnaud 1996).[1]

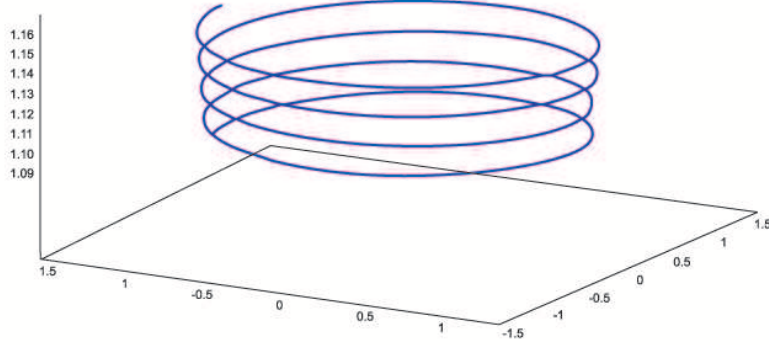


FIGURE 3. Plunging trajectory of a photon into the event horizon of an extreme Black Hole

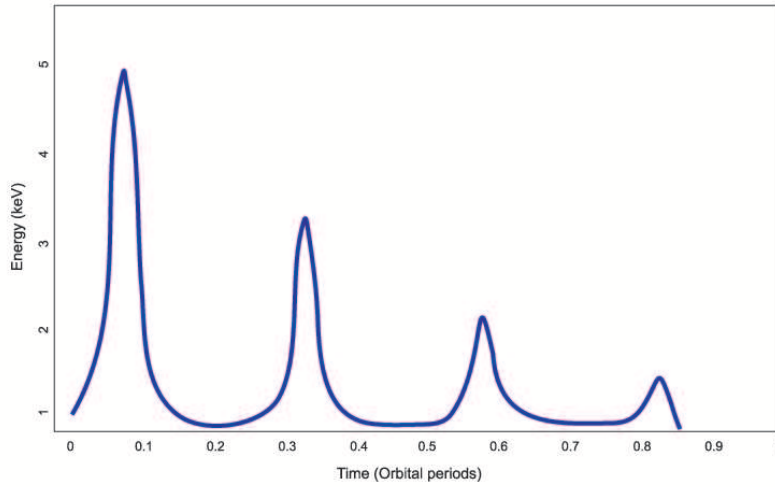


FIGURE 4. Light curve of an in-falling spot near to the horizon of an extreme Kerr black hole, with spin parameter $a=0.998$. Energy is on the ordinate, time on the abscissa.

DISCUSSION

We try to address several questions concerning the validity of the simple spot model and the role of the relativistic effects in the observed processes. We calculate time-dependent spectra of both cases of an orbiting and a free falling spot. The code integrates the local emission in polar coordinates on the disc, enabling us to handle non-stationary emission originated in a non-axisymmetric area of integration.[8] In the axisymmetric case, the local emission is integrated in one dimension, the radial coordinate of the disc.[17]

We are able to:

1. gather information about the black-hole spin
2. study plunging photon trajectories starting at the marginally stable orbit down

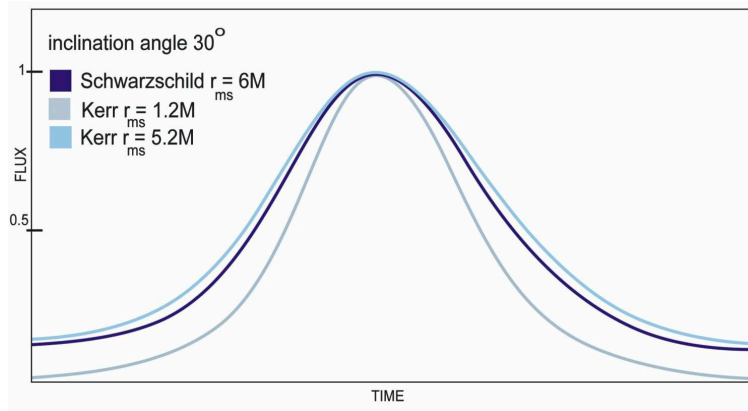


FIGURE 5. Comparison between Kerr and Schwarzschild black hole light curves

towards the black hole event horizon. This provides us with information about the plunge region, the area between the Event Horizon and the last stable orbit.

3. work with the emissivity as dependent on both of the polar coordinates within the equatorial plane
4. deal with time variable spectra, therefore handle non-stationary cases, making possible the study of the time evolution of the emitting region.
5. study light curves for different inclination angles of the observer relative to the disk axis (θ_0) and analyze the dependence of the variability on the inclination.
6. choose a non-axisymmetric emission area, therefore control the size and shape of the spot
7. consider non-axisymmetric geometry of accretion flows
8. analyze the general and special relativity effects that influence photon paths along null geodesics towards an observer located at infinity [16]
9. as the photon paths are integrated in Kerr ingoing coordinates, this allows us to study the Kerr geometry and test the metric

Emission starts within a localized area at the surface of the accretion disc.[18] We consider two cases, whether the spot moves with a Keplerian velocity along a stable circular orbit or, if close to the last stable orbit, it plunges into the black hole.[6] The intrinsic intensity at each point depends on the energy shift of the photons and it is time dependent.

Photons emerging from the spot would be affected by all relativistic imprints. [4] The KYSPOT code by Dovciak et al. takes all special and general relativistic effects into account by using pre-calculated sets of transfer functions that map various properties of the emission region in the accretion disk onto the sky plane (Cunningham 1975, 1976). Six functions are needed for the complete integration of the spectra of the emission region.

The transfer function, obtained by integration of the geodesic equation, correlates the flux in the local frame comoving with the disk, to the flux as seen by the observer located at infinity. [25] Spectral line profiles are obviously affected by relativistic smearing but

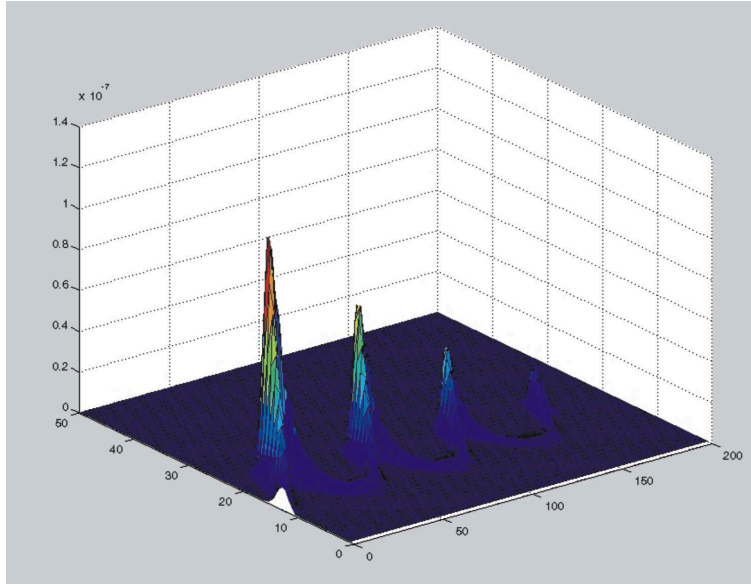


FIGURE 6. Dynamic spectrogram of a plunging spot around a Kerr black hole. The profile includes variations in the redshift of the emitted light.

due to the power-law character of the relativistic imprints, the main shape of the primary continuum profile remains intact.[24]

The functions are calculated for different values of observer inclination angle and black hole horizons. The binary extensions contain information for different radii and different values of g -factor, defined as the ratio between the photon energy observed at infinity and the local photon energy as emitted from the disc. Because the emission from the disc is not stationary we take into account the relative delay with which photons from different parts of the disc arrive to the distant observer.

We obtain time-dependent spectra for various viewing directions of a distant observer based on different emissivity profiles and various angular momenta of the black hole. The relativistic corrections on the local emission are parameterized by the black hole spin and the observer's inclination angle.[14] The intrinsic emissivity is specified in the frame co-moving with the disc medium and it is defined as a function of r , ϕ and t in the equatorial plane. When the geodesic integration is ended, after the transfer of photons to the distant observer is performed, Boyer-Lindquist coordinates will replace the initial Kerr ingoing coordinate system. [12] The observed spectra depend on the position of the spot with respect to the disk normal. We obtain light curves of the variable emission region, for different positions and angles (azimuthal and polar) of the spot relatively to the distant observer, the event horizon and the center of the disk. We also consider different spin parameter values, various viewing angles and different sizes of the emitting spot.

REFERENCES

1. Arnaud K. A., 1996. XSPEC: The first ten years. In *Astronomical Data Analysis Software and Systems V*, eds. Jacoby G. & Barnes J., ASP Conf. Series, vol. 101, p. 17
2. Beckwith K., & Done C., 2004. Iron line profiles in strong gravity. *MNRAS*, in press (astro-ph/0402199)
3. Carter B., 1968. Global structure of the Kerr family of gravitational fields. *Phys. Rev.*, 174, 1559
4. Chandrasekhar S. 1960. *Radiative Transfer*. Dover publications, New York
5. Chandrasekhar S., 1992. *The Mathematical Theory of Black Holes*. New York, Oxford University Press
6. Connors P. A., & Stark R. F., 1977. Observable gravitational effects on polarized radiation coming from near a black hole. *Nature*, 269, 128
7. Connors P. A., Piran T., & Stark R. F., 1980. Polarization features of X-ray radiation emitted near black holes. *ApJ*, 235, 224
8. Dovčiak M., 2004. PhD Thesis (Charles University, Prague)
9. Dovčiak M., Karas V., & Yaqoob T., 2004. An extended scheme for fitting X-ray data with accretion disc spectra in the strong gravity regime. *ApJS*, 153, 205
10. Fabian A. C., Iwasawa K., Reynolds C. S., & Young A. J., 2000. Broad iron lines in active galactic nuclei. *PASP*, 112, 1145
11. Fanton C., Calvani M., de Felice F., & Čadež A., 1997. Detecting accretion discs in active galactic nuclei. *PASJ*, 49, 159
12. George I. M., & Fabian A. C., 1991. X-ray reflection from cold matter in active galactic nuclei and X-ray binaries. *MNRAS*, 249, 352
13. Ghisellini G., Haardt F., & Matt G., 1994. The contribution of the obscuring torus to the X-ray spectrum of Seyfert galaxies – a test for the unification model. *MNRAS*, 267, 743
14. Gierliński M., Maciolek-Niedźwiecki A., & Ebisawa K., 2001. Application of a relativistic accretion disc model to X-ray spectra of LMC X-1 and GRO J1655-40. *MNRAS*, 325, 1253
15. Kato S., Fukue J., & Mineshige S., 1998. *Black-Hole Accretion Discs*. Kyoto, Kyoto Univ. Press
16. Krolik J. H., 1999. *Active Galactic Nuclei*. Princeton University Press, Princeton
17. Laor A. 1991. Line profiles from a disc around a rotating black hole. *ApJ*, 376, 90
18. Martocchia A., Karas V., & Matt G., 2000. Effects of Kerr space-time on spectral features from X-ray illuminated accretion discs. *MNRAS*, 312, 817
19. Matt G., Perola G. C., & Piro L., 1991. The iron line and high energy bump as X-ray signatures of cold matter in Seyfert 1 galaxies. *A&A*, 247, 25
20. Matt G., Perola G. C., Piro L., & Stella L., 1992. Iron K-alpha line from X-ray illuminated relativistic discs. *A&A*, 257, 63; *ibid.* 1992, 263, 453
21. Misner C. W., Thorne K. S., & Wheeler J. A., 1973. *Gravitation*. San Fransisco, W.H.Freedman & Co.
22. Novikov I. D., & Thorne K. S., 1973. In *Black Holes*, eds. DeWitt C., DeWitt B. S. New York, Gordon & Breach, p. 343
23. Rauch K. P., & Blandford R. D., 1994. Optical caustics in a Kerr space-time and the origin of rapid X-ray variability in active galactic nuclei. *ApJ*, 421, 46
24. Reynolds C. S., & Nowak M. A., 2003. Fluorescent iron lines as a probe of astrophysical black hole systems. *Phys. Rep.*, 377, 389
25. Schnittman J. D., & Bertschinger E., 2004. The harmonic structure of high-frequency quasi-periodic oscillations in accreting black holes. *ApJ*, 606, 1098
26. Walker M., & Penrose R., 1970. On quadratic first integrals of the geodesic equations for type {2,2} spacetimes. *Commun. Math. Phys.*, 18, 265